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MRL CONFINED SHEAR TEST METHOD

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MRL CONFINED SHEAR TEST METHOD

by

M. Gyenge*

ABSTRACT

This report provides a detailed account of the development and verification of a novel testing concept for establishing the frictional and strength properties of jointed rocks.

A set of four cylindrical specimens is easily prepared from readily available diamond drill cores. In the test apparatus, three equal normal forces are applied on the three outside specimens in a radial direction. The latter are in sliding contact with the central specimen along three equally-spaced generatrices. A concentric shear force is applied to the central core in an axial direction. The central core is free to move along the shear direction, but it is otherwise confined along the lines of contact, by the statically most stable triangular application of normal forces.

The technique has been verified so far by successfully testing several types of rock as well as other materials. Strength and frictional properties were determined both for smooth joints and for joints with simulated asperities.

The results obtained from the completed tests revealed that this technique is superior of any of the previously-used shear testing methods. Due to the inherent advantages of the applied concept and procedures, a large quantity of highly reliable joint-property data can be obtained from a single set of test specimens.

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Based on the reliable, reproducible and consistent data thus obtained, it is seemingly possible to evolve a data analysis method required to define, and to distinguish between, the various components of the coefficient of friction, and the relationships between these components.

The test apparatus, due to its simplicity, is highly versatile. It can be used not only in conjunction with a laboratory press, but also with a simple portable test frame operated by hydraulic hand pumps. The necessary specimen preparation can also be performed on site at the mines.

TECHNIQUE D'ESSAI DE CISAILLEMENT EXCLUSIVE AUX LSM

par

M. Gyenge*

RÉSUMÉ

Dans ce rapport l'auteur donne une description détaillée du développement et du contrôle d'un nouveau concept d'essai visant à déterminer les propriétés de résistance au cisaillement et à l'usure par le frottement, de roches crevassées.

Un ensemble de quatre échantillons cylindriques est aisément préparé à partir de carottes obtenues par le forage au diamant. Dans l'appareillage d'essai, trois forces égales sont appliquées dans le sens radial au trois échantillons de trouvant à l'extérieur. Ces échantillons sont en contact glissant avec l'échantillon central qui a été disposé le long des trois génératrices qui se trouvent à égale distance les unes des autres. Une force de cisaillement concentrique est appliquée dans le sens axial à la carotte qui se trouve au centre. Celle-ci peut se déplacer dans le sens du cisaillement mais est contrainte à demeurer le long des points de contact par l'application triangulaire, statiquement plus stable, de forces ordinaires.

À ce jour, la technique a été vérifiée par l'essai fructueux de plusieurs types de roches et autres matériaux. Les propriétés de résistance au cisaillement et à l'usure par le frottement ont été déterminées en ce qui concerne les joints lisses et les joints qui, par simulation, présentent des aspérités

Les résultats obtenus à la fin des essais indiquent que cette technique est supérieure à toute autre technique d'essai de cisaillement

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utilisée auparavant. En raison des avantages inhérents à l'application du concept et au mode opératoire, une quantité de données très fiables sur les propriétés des joints peut être obtenue au moyen d'un seul ensemble d'échantillons.

En se basant sur des données fiables, consistantes et qui peuvent être reproduites, il semble possible d'élaborer une méthode d'analyse des données pour définir et établir la distinction entre les diverses composantes du coefficient de friction et les liens entre ces composantes.

En raison de sa simplicité, l'appareillage d'essai offre une grande versatilité et peut être utilisé conjointement non seulement avec une presse de laboratoire mais également avec un banc d'essai activé au moyen de pompes hydrauliques manuelles. La préparation des échantillons peut également être faite sur place, à la mine.

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INTRODUCTION

An increasing amount of Canadian underground mining will, in the future, take place under high stress, deep mining conditions. The increasingly sophisticated analysis, needed for the proper mine design, will require even more accurate constitutive equations to describe the strength and deformational properties of the rock mass. Consequently, new test methods and analytical procedures have to be developed to provide sufficiently accurate test data for use in underground rock mechanics investigations, and in design and ground control calculations.

The measurements of frictional strength along joints are of fundamental importance. The reliability of test data, obtained by the presently used shear test methods, however, are often questionable.

To reliably establish the frictional and strength properties of rock joints, a new testing technique had to be developed. This report is an account of this development and of the verification procedures involved in the novel testing concept, which will be referred to as the "MRL Confined Shear Test Method".

PRESENT TEST METHODS

The frictional and strength properties of joints are currently determined by either triaxial or direct shear test methods.

The triaxial method is used to establish the shear strength of a geological discontinuity in a cylindrical specimen under triaxial loading. This test provides data useful in determining the strength properties of the natural discontinuities, namely peak shear strengths at various lateral pressures, plus the peak value of the coefficient of friction and of the apparent cohesion. The test is performed on a cylindrical rock specimen containing a single geological discontinuity with a certain degree of surface roughness and with an angle of orientation permitting sliding under the triaxial test conditions.

The limitation in the degree of surface roughness that can be tested represents one of the drawbacks of the method. The orientation requirement poses both a further limitation on the use of the method, and also problems in specimen preparation. A distinct advantage of the method is that triaxial

test conditions are used. This permits the frictional and strength properties of the tested discontinuity to be obtained under confinement, i.e., under conditions which may simulate the actual field conditions around an underground opening.

The more popular of the two current methods in use is the direct shear test. The laboratory test is performed in a shear device consisting of a box made of two frames that hold the two halves of the specimen, separated by the plane of discontinuity. The test provides data useful in determining the strength properties of the natural discontinuities. The following relevant information is provided: (a) the shear strength on the plane at various normal pressures; (b) the geometrical component of the shear strength which results from the interlocking of surface irregularities; and (c) the frictional component of the shear strength due to sliding of the two surfaces. The test can be performed on a rock specimen of either irregular or cylindrical shape which contains the particular discontinuity of interest.

The shear device is provided with means for applying a normal force to, and a shearing force along, the plane of discontinuity. The test method simulates the sliding condition of a surface block which is unconfined along its sides.

A specific type of direct shear test method is used to determine the residual shear strength and residual angle of friction of a rock substance. The test is usually performed on cylindrical specimens with a saw-cut plane of discontinuity. The test is used: (a) either to complement the triaxial shear tests which provide data relating only to the peak strength properties; or (b) to check the residual angle of friction of a natural discontinuity in the rock which is obtained by calculation from a direct shear test along the natural discontinuity.

A field version of the direct shear method is used to measure the in situ peak and residual shear strengths as a function of the stress normal to the sheared plane. This test is usually employed in connection with foundation investigations of large structures, when the resulting test expenses can be justified.

The field shear tests are carried out on intact blocks of the rock in question, which are isolated from the surrounding rock mass by excavation, or by drilling. The size of a block sample is governed by the capacities of the available loading systems. While a 0.1 m^2 area of tested discontinuity

can be taken as a minimum, tests on a larger scale are expected to provide more representative results. A distinct disadvantage of the field shear test is the necessary costs involved in site preparation and the rather complex and large loading facilities required.

Regardless of the test method used, interpretation of the test results and their use for underground designs provide only uncertain answers. The uncertainties are inherent in the test method itself. The following problem areas are common to all of the specific tests mentioned above.

One of the interpreted laws of friction postulates that, in the case of dry surfaces, the friction force is not dependent upon the total area of the surfaces in contact. Therefore, these methods should provide reliable data. However, problems arise at the stage of shear and normal stress calculations. The original contact area can, perhaps, be calculated or measured. Once the normal and shear forces are applied, however, and once the normal and shear displacements have occurred, the original contact area changes and is no longer known. An analysis, interpretation and use of the test results is, therefore, questionable.

Another interpreted law of friction states that, in the case of dry surfaces, the friction force is dependent upon the kinds of materials tested and upon the degree of roughness of the two surfaces in contact. However, to establish the strength and frictional properties along a plane of discontinuity, at least three, and preferably five, data pairs of the normal and shear stresses are required. Therefore, ideally, an equivalent number of individual tests must be conducted at a range of normal loads, on specimens of identical material and of an equal degree of roughness along the two surfaces in contact. When dealing with geological materials, it is hard enough to meet the first requirement. The identical surface roughness of contact criterion probably never occurs. The test results obviously reflect the differences between the specimens, which in turn contributes to the uncertainty in the results achieved.

The third interpreted law of friction states that the maximum friction force which can be developed is dependent upon the normal pressure between the two surfaces in contact, and is proportional to it. One problem tied in with this law is the uncertainty with which the normal pressure can be established. Because the contact area continually changes during the test, and since there is also a variation in the surface roughness along the contact area, the normal pressure cannot be calculated with any degree of certainty.

The second problem is related to the magnitude of the normal stress which is usually applied when using these test methods. In order to run the tests on sliding surfaces that contain all of the representative features of the relevant discontinuity, the goal is to select its area as large as possible. However, due to the constraints imposed by the capacities of the available loading devices, the tests are usually performed at rather low levels of normal stress. Consequently, the strength and frictional properties in case of higher normal stresses can only be estimated by the very uncertain means of extrapolation.

There are other shortcomings of these test methods as well. One such shortcoming, already touched upon, is related to the question of field-condition simulation. The failure mechanism due to the sliding of rock blocks, forming the periphery of an underground opening or the surface of an open pit, is adequately simulated by these methods. However, the movement of blocks within the rock mass is constrained. This condition is simulated only by the triaxial test method; this, however, has its own drawbacks, as discussed previously.

Moreover, specimen preparation for these tests is rather difficult, especially in the case of the in situ shear test. Also, with the exception of the portable shearing device, the required special testing facilities are relatively complex.

Contact area related problems are eliminated by the test method suggested by Stimpson [1]. This simple test procedure measures the critical angle of sliding of cylindrical core surfaces in contact, by using three pieces of core and a tilt table. The main problem with this method is that the frictional properties can only be established for a smooth surface and for a single normal load, namely, for the weight of the sliding core.

CONFINED SHEAR TEST METHOD

BASIC PRINCIPLE

The basic principle of the confined shear test technique is illustrated in Fig. 1. The specimen set comprises four cylindrical rock core specimens of identical diameter. The three outside specimens are of equal length, while the centre core is longer.

Each of the outside cores is loaded by a normal force, P_N, of equal magnitude. The concentric shear force, S, is applied to the centre core.

The outside cores are all rigidly supported from both underneath and behind; therefore, their movement in a vertical direction, i.e., in the direction of shearing, is constrained. However, their individual horizontal movement, i.e., their normal displacement, is unconstrained. The centre core, which moves freely in the vertical direction, is supported only by the shear and normal forces along the three vertical lines of contact with the outside cores.

In addition, the horizontal movement of the core set as a whole is unhindered. This provision of free movement is a further guarantee of the concentric application of the shear force. By virtue of the statically very stable triangular application of the normal forces, and the provision of free movements, a completely self-adjusting loading system is attained.

The diagram of forces is shown in Fig. 1(b). The centre core is confined laterally by the radially-applied normal forces, P_N. Axial displacement, i.e., shear displacement, of the centre core occurs when the applied shear force, S, is greater than the combined shear resistance along the three lines of contact with the outside cores. Equilibrium is reached when

$$\frac{S}{3\mu} = P_N \qquad \text{Eq 1}$$

let

$$P_S = \frac{S}{3} \qquad \text{Eq 2}$$

therefore,

$$\frac{P_S}{\mu} = P_N \qquad \text{Eq 3}$$

and the coefficient of friction is:

$$\mu = \frac{P_S}{P_N} \qquad \text{Eq 4}$$

TEST APPARATUS

The test apparatus was developed and constructed in-house at the RML [2]. It is shown in Fig. 2 and 3.

The main component of the apparatus is its ring-frame. It contains three grooves, spaced at 120° along the inside diameter, to accommodate the vee blocks which are to seat the outside cores. At the groove locations, the ring-frame also contains through-holes equipped with hydraulic pistons. The ring-frame is carefully levelled by three levelling bolts, positioned at 120°.

The three through-holes, with the pistons inside them, are connected to the hydraulic power supply by a common line.

The ring-frame, is supported by three levelling bolts in an elevated and levelled position. The bolts rest on a polished steel plate. The vee blocks within the grooves are also resting on the polished steel plate. Underneath they are lubricated to facilitate normal displacement of the outside core. The vee blocks are L-shaped in their vertical cross-section, to allow for the support and vertical positioning of the outside cores.

Normal Force Application

The hydraulic pistons are activated by the pressurized hydraulic fluid in the common line. In the RML laboratory the line is pressurized from the confining pressure unit of the press. In field use, a hydraulic hand pump can be employed.

The activated pistons push the vee blocks, guided by the grooves, towards the centre of the assembly. The triangular loading arrangement and equal piston forces ensure that the three outside cores are loaded equally. Therefore, the applied normal forces along the contact lines (between the centre sliding core and the side cores) are also equal. Due to the applied lubrication, the radial movement of the vee blocks is virtually frictionless. Therefore the applied load is evenly distributed as a line load, along the entire length of the contact lines.

The evenly-distributed normal force is directly proportional to the applied line pressure. The desired pressure is kept constant manually.

Measurement of Normal Displacement

The arrangement to measure normal displacement is shown in Fig. 3 and 4. A short pin is fastened to the top of each vee block. A very thin copper

wire interlinks these pins. At one end the wire is fixed to one of these pins, while passing over the other two pins. The other end of the wire is fastened to the core of a LVDT. The LVDT is, in turn, securely clamped to the ring-frame.

The average normal displacement, be it dilation or contraction, can then be calculated for every test stage from the recorded movement of the LVDT core, by taking into consideration the geometry of the wire linkage.

The completed tests showed, however, that measurements obtained with this arrangement did not always provide an accurate reading of the normal displacement. The reason is quite clear. In order to ensure concentric shear force application, as mentioned before, the set of cores, as a whole, is allowed to move sideways. However, since the position of the LVDT is fixed (it being clamped to the ring-frame) any floating movement of the entire core set is added to the measured sum of the normal displacements, occurring along the lines of contact.

If required, an accurate normal displacement measurement can be achieved by means of a simple modification. Small LVDT units can be placed within drill holes in the ring-frame, appropriately positioned at each groove, with the purpose of measuring the individual displacement of each vee block. These displacements would then be an accurate measure of the individual normal displacements that occur along the three lines of contact.

The necessity for improved accuracy in normal displacement measurement became highly questionable, however, after analyzing the test results. The magnitude of the normal displacement is not required for the analysis of strength and frictional properties. The existing system, as described, indicates whether the observed displacement is due to dilation or to contraction. This information is adequate to analyze the shear mechanism occurring during various phases of the test.

Shear Force Application

The test set-up in conjunction with the laboratory press, and with the portable field press is shown in Fig. 5 and 6, respectively. The axial load is supplied by the loading system of the press in the first instance. In the second case a hydraulic jack, activated by a hand pump, does so.

The shear force acting on the sliding centre core is measured and recorded by the strain-gauged ring load cell.

Measurement of Shear Displacement

The shear displacement is measured and recorded by a vertically-positioned LVDT. It is held in a vertical position by a horizontal arm which is connected to a cylindrical steel loading platen. This platen is located between the sliding centre core and the load cell.

The tip of the spring-loaded extension rod of LVDT core is rests on the ring-frame.

Data Recording

The outputs of the transducers (i.e., of the strain gauges of the load cell, of the LVDT for normal displacement and of the LVDT for shear displacement) are recorded by an XY_1Y_2 recorder on data sheets with convenient grids.

The shear force versus normal displacement relationship is recorded on XY_1 axes. Test data with respect to the shear force versus shear displacement are recorded on the XY_2 axes.

PREPARATION OF SPECIMEN SET

The test requires a set of four rock cores of identical diameter. The test apparatus is designed for the preferred BX size cores (i.e., with a nominal diameter of 41.3 mm). However, specimen sets with a somewhat larger or smaller diameter are also acceptable.

Although the length of the core is not an essential dimension, the preferred length to diameter ratio for the outside cores is 2:1. The height of the sliding centre core is increased by the desired length of the shear displacement. Based on the results of the completed tests, the preferred shear displacement is in the order of 15 mm.

The parallel ends are cut perpendicular to the axis by a circular diamond saw. No special end preparation is necessary.

The core surface obtained by typical core-drilling procedures is acceptable for routine tests. However, the core surface is to be specially prepared if the test is aimed at simulated surface roughness investigation.

A smoother than core-drilled surface can be obtained, for example, by surface grinding in a machinist-lathe (Fig. 7). The simulated large surface asperities are prepared in the same way. The matching intrusions and protrusions of the simulated asperities are formed on the rotating cores by grinding wheels having the desired profile.

One of the most important advantages of this test method is that each specimen set can be tested at several different levels of normal force. Each test, at the predetermined normal force level, is performed along a specific set of contact lines. The cores are rotated after each test. The predetermined test lines, together with the respective test number and core identification, are marked on the round labels attached to the top surface of the cores (Fig. 3 and 4).

The maximum number of tests that can be conducted on the same set of cores is governed by the diameter of the cores and by the extent of shear and crushing damage experienced along the lines of contact. The damage depends upon the normal force of the test run.

Experiments with BX size cores show that in the case of smooth core surfaces (core-drilled, ground, and lapped) up to nine tests can be performed on the same specimen set. The number of tests on cores with simulated large asperities must, however, be decreased to four, to avoid overlapping damage to the asperities.

TEST PROCEDURES

The reliability and usefulness of the MRL Confined Shear Test Method has been verified by performing a comprehensive test program.

The objectives of the test program were:

(a) to verify the concept;
(b) to determine the accuracy and reproducibility of the data thus obtained;
(c) to establish the test procedure which will provide the largest amount of reliable test data;
(d) to establish the strength and frictional properties of a set of smooth joints in the same rock material, with minor variations in smoothness;
(e) to establish the strength and frictional properties of various materials, with similar joint smoothness;
(f) to establish the strength and frictional properties of joints with simulated asperity;
(g) to determine the various components that add up to the overall coefficient of friction; and

(h) to determine the most promising direction of further development and research within the general area of subject techniques.

The results of the successfully completed test program are detailed in Division Report MRP/MRL 85-62(INT) [3].

The test program used two types of test procedures, namely: single-stage procedure and multi-stage procedure.

SINGLE-STAGE PROCEDURE

The feature of the single-stage procedure is that along each set of contact lines only one shear test is performed. Various predetermined normal force is applied to each set of contact lines, which is kept constant for the test run.

The steps of the test procedure are explained by referring to Fig. 8, which is the XY_1Y_2 recording of a complete confined shear test. On the same Indiana limestone specimen set, with diamond drill surface finish, nine shear test runs were conducted along nine different sets of contact lines. The various applied normal forces (P_N) of each test run are marked in Fig. 8.

The shear force (P_S) and shear displacement (δ_S) relationship are represented by the XY_2 records in the lower part of Fig. 8. The corresponding shear force (P_S) versus normal displacement (δ_N) graphs are given in the upper part of Fig. 8.

To obtain a clean set of graphs, it is suggested that, as the test proceeds, the normal forces be applied in an increasing order.

For the sake of consistency it is recommended that the same steps be followed for each test run. In the case of the first run, of the subject test presented in Fig. 8, these steps are as follows:

(a) Setting of contact lines - While the centre core rests on a spacer block and the outside cores are seated on the vee blocks, the cores are rotated until the respective No. 1 markers on the labels are matched up.

(b) Application of normal force - The hydraulic pistons are activated until the predetermined line pressure is reached. In this given case, this amounts to 500 psi (3.45 MPa) providing a normal force of 41.6 lbf (185 N) with the given piston areas.

(c) Mounting of instruments - The LVDT transducers, as well as the strain-gauged ring load cell, are positioned and connected to the XY_1Y_2 recorder. The spacer block, supporting the centre core, is now removed.

(d) Setting of data recording procedures - The scales of the recording instrument are set, and the recording pens are moved and lowered into their recording positions. The cross-head of the press is lowered.

(e) Application of shear force - While the normal force is kept constant, the shear force is applied at a constant rate until the predetermined amount of shear displacement is reached. The latter is 0.35 in. (9 mm) in case of subject test runs.

(f) Dismantling - First the shear force is released and the cross-head of the press raised. Then the transducers are dismantled next, the spacer block is placed underneath the centre core, and finally the normal force is released.

The high quality of the data obtained by the MRL Confined Shear Test Method is evident from even a cursory observation of the graphs presented in Fig. 8. The overall shape of each graph is the same. The initial portion of each P_S versus δ_S graph is characterized by a slightly-curved line. Up to the level of shear force that occurs at the end points of these initial phases, there is no shear displacement. The slight curvature is due to elastic deformation. The roughly vertical portions, that follow, reflect the variations in the shear force due to the shearing mechanism along the particular contact lines. The extent of the variations depends upon the interaction between the minute asperities along the "smooth" contact lines.

The P_S versus δ_N graphs show a similar consistency. It has been discussed previously, that the measuring technique used did not always provide an accurate reading of the normal displacement. In the case of these test runs the normal displacement values obtained, however, are found to be accurate. They could be used, should they be required for the analyses.

But, as was also pointed out, the exact magnitudes of the normal displacements for establishing the strength and frictional properties of the joints are not necessary. Knowledge of the general nature of the normal displacements is, however, a useful piece of information when analyzing the overall shear mechanism. From the P_S versus δ_N graphs of Fig. 8, it is quite evident that, in case of these test runs, a contraction took place. Contraction indicates crushing of the minute asperities along the contact lines.

Specimen sets with smooth surface finishes can be tested either by single-stage or multi-stage procedures. However, to test specimen sets with simulated large asperities, the single-stage procedure must always be used.

MULTI-STAGE PROCEDURE

The multi-stage procedure is used to test specimen sets with smooth surface finish, with the distinct advantage that an increased amount of test data can be obtained from the same set of cores.

Figures 9 to 14 illustrate the complete set of data, obtained by the multi-stage test procedures. The drilled-core specimens were tested along six lines of contact. Each figure corresponds to one of these line contacts.

The procedure is explained by referring to Fig. 9.

The first run with this procedure also follows steps (a) to (f) of the single-stage procedure, as previously specified in connection with Fig. 8. The hydraulic line pressure in this case was 125 psi (862 kPa) which provided a normal force of P_N = 10.4 lbf (46 N). The shear displacement for the first run was 0.6 in. (15 mm).

The P_S versus δ_S graph thus obtained is shown in the left-hand side of Fig. 9. The uppermost graph is the corresponding P_S versus δ_N graph.

The remaining steps of a test run by the multi-stage procedure are as follows:

(g) Re-application of the normal force - A repeat of step (b).

(h) Re-mounting of all instruments - A repeat of step (c).

(i) Re-setting of data recording procedures - A repeat of step (d).

(j) Application of shear force - While the normal force is kept constant, a shear force is applied at a constant rate until shear displacement of 0.1 in. (2.5 mm) is reached.

(k) Increase of normal force - While the shear force is kept constant, the line pressure is swiftly increased to the next predetermined level. In case of Fig. 9, this level is 250 psi (1.7 MPa) which produced the normal force of P_N = 20.8 lbf (93 N).

(l) Continuous application of shear force - While the normal force is kept constant at the new level, a shear force is continuously applied at a constant rate until an additional shear displacement of 0.1 in. (2.5 mm) is reached.

(m) Repeat steps (k) and (l) at the additional predetermined normal force levels. In the case of Fig. 9, these were:

P_N = 41.6 lbf (185 N)

P_N = 83.2 lbf (370 N)

P_N = 166.4 lbf (740 N)

P_N = 416.0 lbf (1850 N)

(n) Dismantling - A repeat of step (f).

The P_S versus δ_S relationship for the multi-stage procedure is shown by the lower graph of Fig. 9. The corresponding P_S versus δ_N graph indicates the increased amount of crushing of minute asperities along the contact line as the normal force levels are increased.

The graphs presented in Fig. 10 to 14 are the test results obtained along test lines from 2 to 6, respectively.

ANALYSIS OF TEST DATA

The detailed analysis that follows is based on the results obtained with the test series presented in Fig. 9 to 14.

The coefficient of friction is a dimensionless number. It is the ratio between the shear and normal forces, as expressed by the equation:

$$\mu = \frac{P_S}{P_N} \qquad \text{Eq 4}$$

The test data being analyzed are the ones obtained from the P_S versus δ_S graphs of Fig. 9 to 14. The indicated applied normal forces (P_N) were kept constant during the test runs. The condition and the interaction of the irregularities along the contact lines vary, though, with the shear displacement δ_S. The shear force (P_S) necessary to maintain a continuous shear displacement, therefore, also varies accordingly.

In Table 1 for each test run the maximum and minimum values of the shear forces, as recorded in each graph in Fig. 9 to 14, are listed in the columns of "High" and "Low", respectively.

In the column of "Initial", is listed the shear force which is required to initiate shear displacement. The "Initial" value of shear force,

as marked for each test run, is defined by the end point of the initial phase of a P_S versus δ_S graph. Generally speaking, for rock materials, this initial shear force falls in between the minimum and maximum values observed during the test runs. However, depending on the conditions of contact, it could be either the maximum or the minimum shear force.

For each data pair the P_S/P_N ratio, i.e., the coefficient of friction, is calculated. The definition of the subscripted μ values in Table 1 are as follows:

μ_s = coefficient of friction of initial sliding - it corresponds to the shear force that is required to initiate sliding;

μ_h = coefficient of friction of high value - it corresponds to the maximum shear force arising during the test run;

μ_l = coefficient of friction of low value - it corresponds to the minimum shear force arising during the test run.

The scatter of these calculated μ values might seem to be considerable for each coefficient, especially for the ones observed with the smaller normal forces. It must be remembered, though, that each value corresponds only to a momentary condition. Therefore, the trend in their variation is more significant than the actual individual momentary value of the coefficient. The average μ values were used in the subsequent steps of this analysis. The average coefficient of friction values of μ_s, μ_h and μ_l are given in Table 1, for each applied normal force level.

The test data in Table 1 are in terms of forces. However, the stability analyses of underground openings, design of support system, mine layout, mining sequence and method studies, etc. are performed in terms of stresses. The strength and frictional properties of joints should, therefore, also be expressed in stress terms. Furthermore, the use of stress terms is also required to correlate the shear test results with other laboratory test data, such as uniaxial and triaxial tests.

The stress along the lines of contact, due to an applied force, P_N, can be calculated by using the solution given by Timoshenko and Goodier [4].

The general solution of pressure between two bodies in contact is applied to the special case of contact of two cylinders with parallel axis. The surface of contact is now a narrow rectangle. The distribution of pressure σ_n along the width of the surface contact is represented by a semi-ellipse.

If b is half of the width of the surface contact, and P_N' is the load per unit length of the surface contact, from the semi-elliptic pressure distribution, one will obtain:

$$P_N' = 0.5 \pi b \sigma_n$$

from which

$$\sigma_n = \frac{2 P_N'}{\pi b} \qquad \text{Eq 5}$$

The investigation of local deformation gives for the quantity b the expression:

$$b = \left(\frac{4 P_N' (k_1 + k_2) R_1 R_2}{R_1 + R_2} \right)^{1/2} \qquad \text{Eq 6}$$

where R_1 and R_2 are the radii of the cylinders and k_1 and k_2 are constants defined by the following equations:

$$k_1 = \frac{1 - \nu_1^2}{\pi E_1} \qquad \text{Eq 7}$$

$$k_2 = \frac{1 - \nu_2^2}{\pi E_2}$$

where ν_1 and ν_2 are the Poisson's ratios and E_1 and E_2 are the elastic modulii of the materials of the cylinders in contact.

Since both cylinders are of the same material and the two radii are equal, Eq 6 is greatly simplified. The value of the Poisson's ratio for the tested Indiana limestone is $\nu = 0.26$, therefore,

$$k_1 + k_2 = 2\left[\frac{1 - 0.26^2}{\pi E}\right] = \frac{0.594}{E}$$

and then

$$b = 1.09\left(\frac{P_N' R}{E}\right)^{1/2} \qquad \text{Eq 6(a)}$$

The calculated normal stresses are summarized in Table 2. In the first column, the applied normal forces are listed in Imperial units. These are converted into SI units in the second column. The third column is obtained by dividing the normal forces by the length of the contact lines, i.e., by $L = 0.07$ m which is the height of the three outside cores. The values in the fourth column are obtained from Eq 6(a) by using $R = 0.021$ m and $E = 33.0$ GPa. The σ_n values in the last column are calculated by using Eq 5.

The data included in the first line of Table 2 were established by the test method suggested by Stimpson [1]. The $P_N = 0.242$ lbf refers to the weight of the sliding core. The photograph of the tilt table with the test cores is shown in Fig. 15.

PRESENTATION OF TEST DATA

The analyzed test data are presented in Fig. 16. The variation of the coefficient of friction values with the normal stresses is plotted in Fig. 16(a). The coefficient friction values are the average values of Table 1. They are plotted against the calculated normal stresses of Table 2.

The variation of the coefficients of the friction of initial sliding (μ_s), of high value (μ_h) and of low value (μ_l), with the normal stress, follows the same pattern. The difference between their values for the lower range of normal stress level is considerable. However, as shown in Fig. 16(b)

this considerable variation in coefficient friction values translates into a rather narrow range of variation in shear stresses.

The shear stress values plotted in Fig. 16(b) are summarized in Table 3. They were calculated by the following equation:

$$\tau = \mu \sigma_n \qquad \text{Eq 8}$$

Shear stresses of τ_s, τ_h and τ_l correspond to initial sliding, maximum and minimum shear stresses, respectively. Characteristically, each stress function begins with a non-linear portion. For the normal stress levels higher than about 30 MPa, however, the stress relationships becomes linear.

The linear stress function from the origin, drawn parallel to the linear portion of stress function τ_s, is designated as the static shear stress, τ_{st}. The corresponding coefficient of friction value of $\mu_{st} = 1.105$ is represented in Fig. 16(a) by a horizontal line.

CONCLUSIONS AND RECOMMENDATIONS

The method described in this report represents a novel testing technique, equally suitable for determining the shear strength of smooth joints and of joints with asperity.

The cylindrical specimens required for the tests are prepared from ordinary diamond-drill cores. Since diamond drilling is the most common sampling technique, drill cores representing rock formations to be investigated are usually readily available. Subsequent specimen preparation work is minimal.

The same specimen set of four cores can be used for several (up to nine) shear tests, which are performed at various applied normal forces. This eliminates the usual variation in shear properties always present when specimens need to be varied. Also, the number of specimens required to establish the shear strength properties of joints for a specific rock formation is greatly reduced.

The test apparatus, incorporating methods for normal and shear force application, represents a self-adjusting self-contained system. This ensures that the normal forces are automatically equalized, and that the applied shear

force is concentric. Thus complete force and displacement control is inherent in the system design.

The three equal normal forces are applied along the three equally spaced contact lines of the central sliding core. This method of load application creates confined test conditions. Therefore, it reproduces the actual field conditions of the rock mass around an underground opening.

The shearing occurs along the contact lines of the cylindrical specimens. Therefore, uncertainties associated with the continuous variations in the magnitude of the actual contact areas during the tests (so characteristic of other shear test methods) are eliminated.

Furthermore, since shearing does take place along the contact lines, the test results thus obtained are only affected by the variation in roughness along the one-dimensional contact lines. Consequently, the results more closely reflect the true frictional properties of the tested material. The influence of the sheared surface quality, unlike other shear test methods, is essentially eliminated.

The novel test principle effectively utilizes the inherent geometrical features of the system. The applied normal loads produce concentrated normal stresses along the contact lines of the cylindrical specimens. Therefore, shear tests can be conducted at much greater normal stress levels than has been possible with any other type of shear test method.

Combination of these advantages resulted in a shear test procedure that yields a large quantity of highly reliable and consistent test data.

Based on the reliable and consistent test data thus obtained, it is seemingly possible to evolve a new data analysis method. With this new method of analysis, in turn, it is seemingly possible to identify and separate the major shear components.

The properly analyzed results of the joint properties tests can also be correlated with the uniaxial and triaxial test data. Consequently, all the major strength and deformation properties of the rocks can be interlinked.

On the basis of the defined interrelationships between the strength properties of the joints and of the rock substance, the shear strength of a jointed rock mass can be established. Both the peak and the residual strength envelopes of a jointed rock mass can be determined, and made practical use of the laboratory test results in the design and stability analysis of underground openings.

In view of its simplicity, the test apparatus is highly versatile. Not only can it be used in a laboratory press, but also it can be used in a portable and simple test frame at the actual mine sites. Normal and shear forces can be provided by hand operated hydraulic pumps. The necessary amount of specimen preparation can also be achieved at the mine sites.

Even though the test apparatus, used for the tests described in this report, was only an in-house-made prototype, it performed very well indeed. The normal displacement measuring device constitutes the only exception. However, the test data analysis procedure proved that measurement of normal displacement is only useful, but not essential. There is, therefore, little need for any modification of the prototype test apparatus.

ACKNOWLEDGEMENT

A considerable number of illustrations was necessary to adequately convey the new testing concept and the procedures used in analyzing the data. They were prepared by J.D. Dugmore. His excellent work is greatly appreciated.

Sincere appreciation is also due to B. Gorski for his excellent and untiring efforts in first producing the test apparatus, and then assisting with the tests.

REFERENCES

1. Stimpson, B. "A suggested technique for determining the basic friction angle of rock surfaces using core"; Int J Rock Mech Min Sci 18:63-65; 1981.

2. Gorski, B. "A multi-shear apparatus"; Division Report MRP/MRL 84-44(TR); CANMET, Energy, Mines and Resources Canada; 1984.

3. Gyenge, M. "Confined shear test method to establish the frictional and strength properties of jointed rocks"; Division Report MRP/MRL 85-62(INT); CANMET, Energy, Mines and Resources Canada; 1985.

4. Timoshenko, S. and Goodier, J.M. "Theory of elasticity"; Engineering Societies Monographs, Second Edition, International Student Edition; pp 381-382; McGraw-Hill Book Co. Inc.; New York; 1951.

Table 1 - List of coefficient of friction values of Indiana limestone

P_N	Test line	Initial		High		Low	
		P_s	μ_s	P_s	μ_h	P_s	μ_l
10.4	1	7.77	0.747	9.25	0.890	5.92	0.569
	2	5.55	0.534	7.77	0.747	4.07	0.391
	3	7.77	0.747	9.99	0.961	6.85	0.658
	4	6.11	0.587	9.44	0.907	4.63	0.445
	5	7.77	0.747	7.77	0.747	3.70	0.356
	6	9.43	0.907	9.43	0.907	3.52	0.338
Average:			0.712		0.860		0.460
20.8	1	16.7	0.801	20.2	0.970	14.8	0.712
	2	15.2	0.729	16.8	0.810	13.3	0.641
	3	16.7	0.801	19.1	0.916	15.2	0.729
	4	18.7	0.898	20.0	0.961	16.7	0.801
	5	15.5	0.747	18.7	0.898	13.0	0.623
	6	13.9	0.667	13.9	0.667	12.4	0.596
Average:			0.774		0.870		0.684
41.6	1	37.6	0.903	41.1	0.987	33.7	0.809
	2	31.8	0.765	36.8	0.885	30.7	0.738
	3	35.2	0.845	43.1	1.036	35.0	0.841
	4	38.9	0.934	42.6	1.023	37.4	0.898
	5	34.8	0.836	35.7	0.858	32.8	0.784
	6	33.9	0.814	35.7	0.858	30.9	0.743
Average:			0.850		0.941		0.801
83.2	1	79.2	0.952	79.2	0.952	72.5	0.872
	2	74.6	0.896	79.6	0.956	72.2	0.867
	3	77.9	0.936	77.9	0.936	70.3	0.845
	4	79.6	0.956	85.5	1.027	78.1	0.938
	5	76.6	0.921	79.6	0.956	74.0	0.890
	6	73.3	0.881	76.0	0.914	71.6	0.861
Average:			0.924		0.957		0.879
166.4	1	162.8	0.979	162.8	0.979	153.2	0.921
	2	159.1	0.956	159.1	0.956	154.7	0.930
	3	163.0	0.980	164.5	0.989	159.5	0.958
	4	170.2	1.023	185.0	1.112	170.2	1.023
	5	166.7	1.002	173.9	1.045	166.7	1.002
	6	162.8	0.979	162.8	0.979	149.7	0.900
Average:			0.987		1.010		0.956
416.0	1	417.1	1.003	421.9	1.014	412.6	0.992
	2	414.5	0.996	423.3	1.018	414.5	0.996
	3	434.8	1.045	454.2	1.092	444.1	1.067
	4	439.6	1.057	439.6	1.057	432.0	1.039
	5	437.2	1.051	448.5	1.079	434.6	1.045
	6	410.8	0.987	420.6	1.011	407.6	0.980
Average:			1.023		1.045		1.020

Table 2 - Calculated normal stresses for Indiana limestone cores

P_N, lbf	P_N, N	P'_N, N/m	b, m	σ_n, MPa
0.242	1.08	15.4	0.34×10^{-5}	2.9
10.4	46.26	660.9	2.24×10^{-5}	18.8
20.8	92.52	1 321.8	3.16×10^{-5}	26.6
41.6	185.04	2 643.5	4.47×10^{-5}	37.6
83.2	370.07	5 287.0	6.32×10^{-5}	53.2
166.4	740.15	10 574.1	8.94×10^{-5}	75.3
416.0	1850.37	26 435.2	14.41×10^{-5}	116.8

Table 3 - Summary of compiled coefficient of friction data and of the calculated shear stresses along smooth joints in Indiana limestone

P_N, lbf	σ_n, MPa	Initial		High		Low	
		μ_s	τ_s, MPa	μ_h	τ_h, MPa	μ_l	τ_l, MPa
0.242	2.9	0.902	2.6	0.916	2.7	0.869	2.5
10.4	18.8	0.712	13.4	0.860	16.2	0.460	8.6
20.8	26.6	0.774	20.6	0.870	23.1	0.684	18.2
41.6	37.6	0.850	32.0	0.941	35.4	0.801	30.1
83.2	53.2	0.924	49.2	0.957	50.9	0.879	46.8
166.4	75.3	0.987	74.3	1.010	76.1	0.956	72.0
416.0	116.8	1.023	119.5	1.045	122.1	1.020	119.1

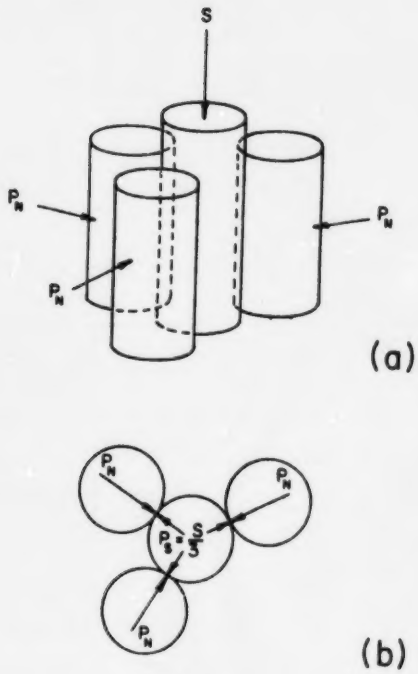

Fig. 1 - Principle of the confined shear test method;

(a) isometric view of specimen set,

(b) top view of specimen set

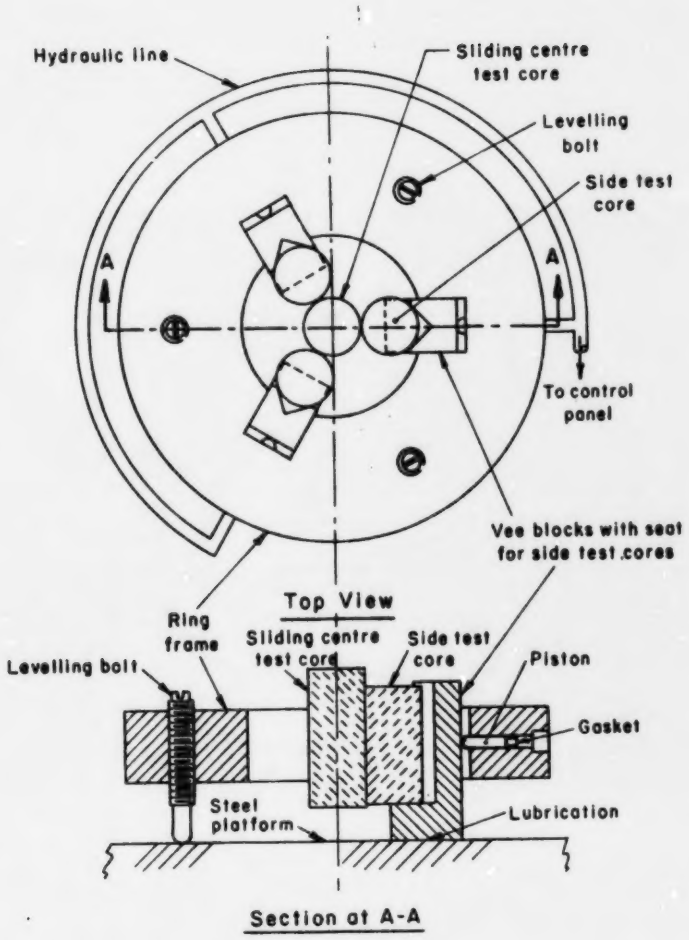

Fig. 2 - Test apparatus; (a) top view, (b) section

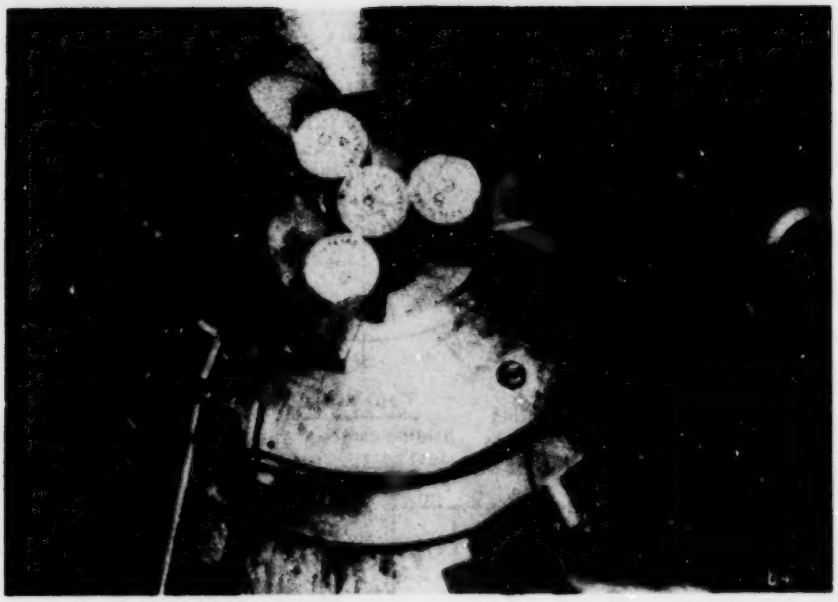

Fig. 3 - Photograph of test apparatus with specimen cores and with device to measure normal displacement

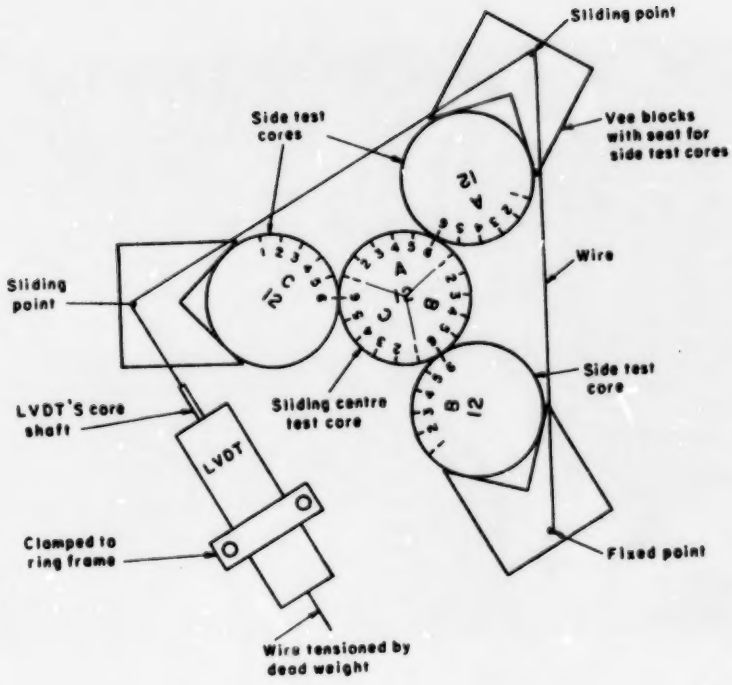

Fig. 4 - Arrangement for measurement of normal displacement

Fig. 5 - Test set-up in conjunction with the laboratory press

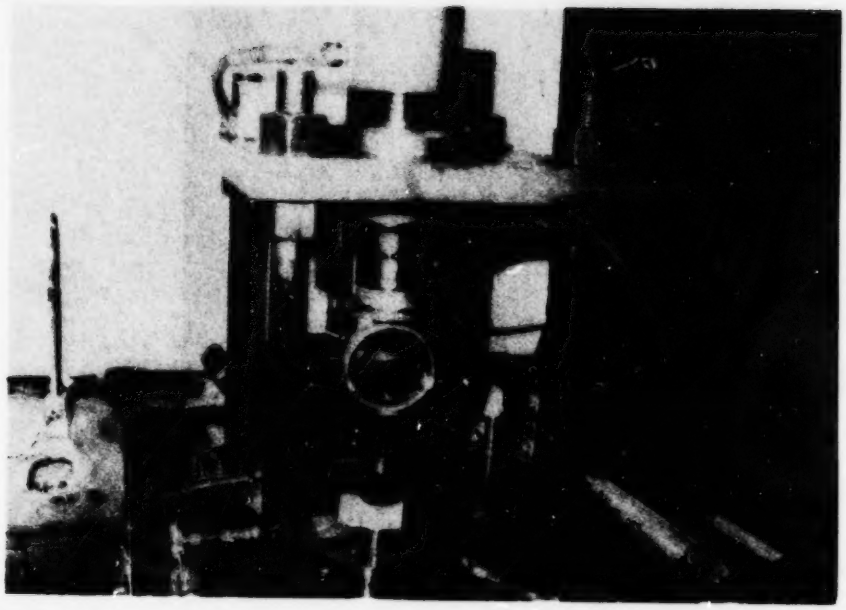

Fig. 6 - Test set-up in conjunction with a portable field press

Fig. 7 - Surface grinding in machinist-lathe

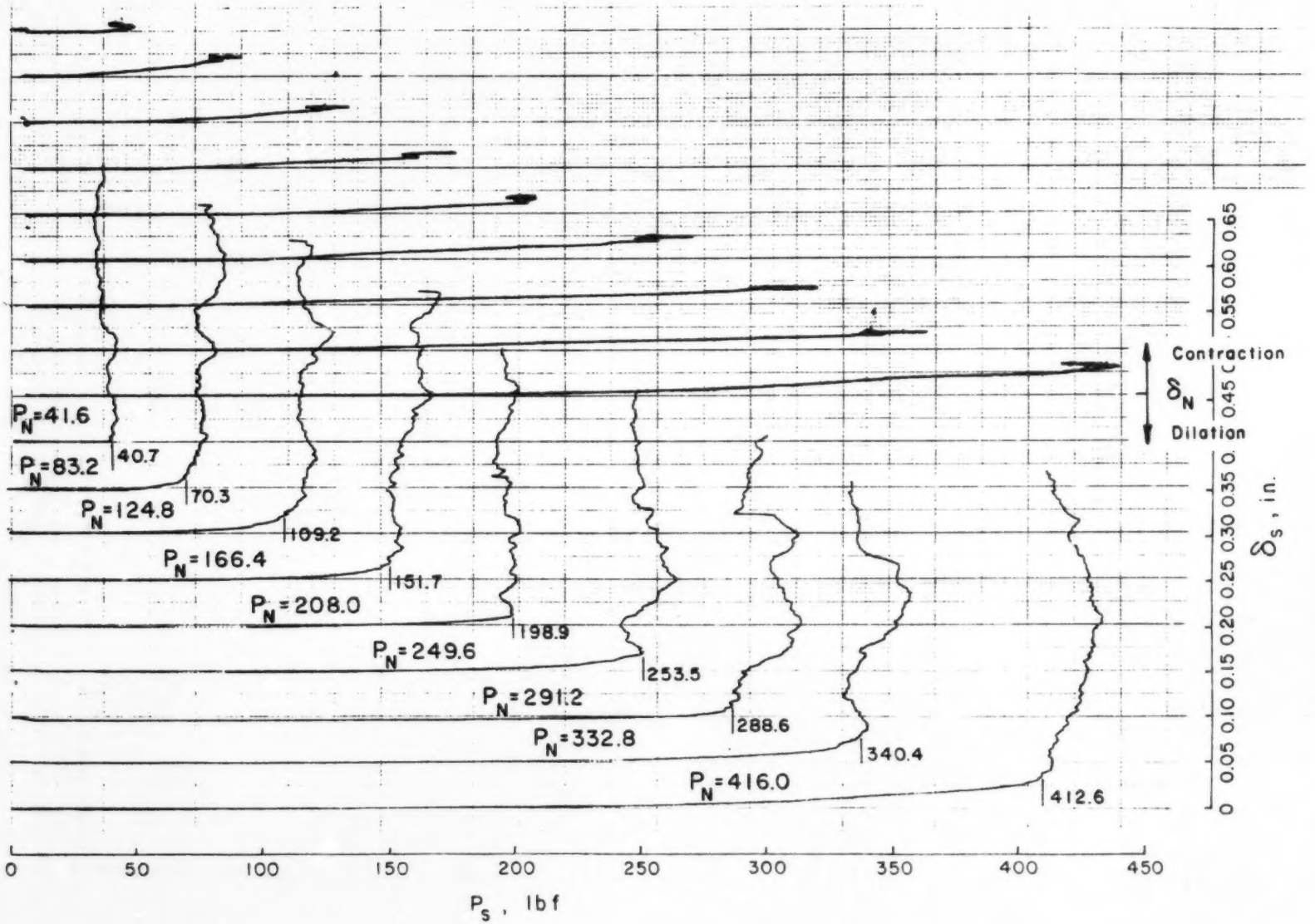

Fig. 8 - Test data, for Indiana limestone with smooth joint, obtained by single- stage procedure

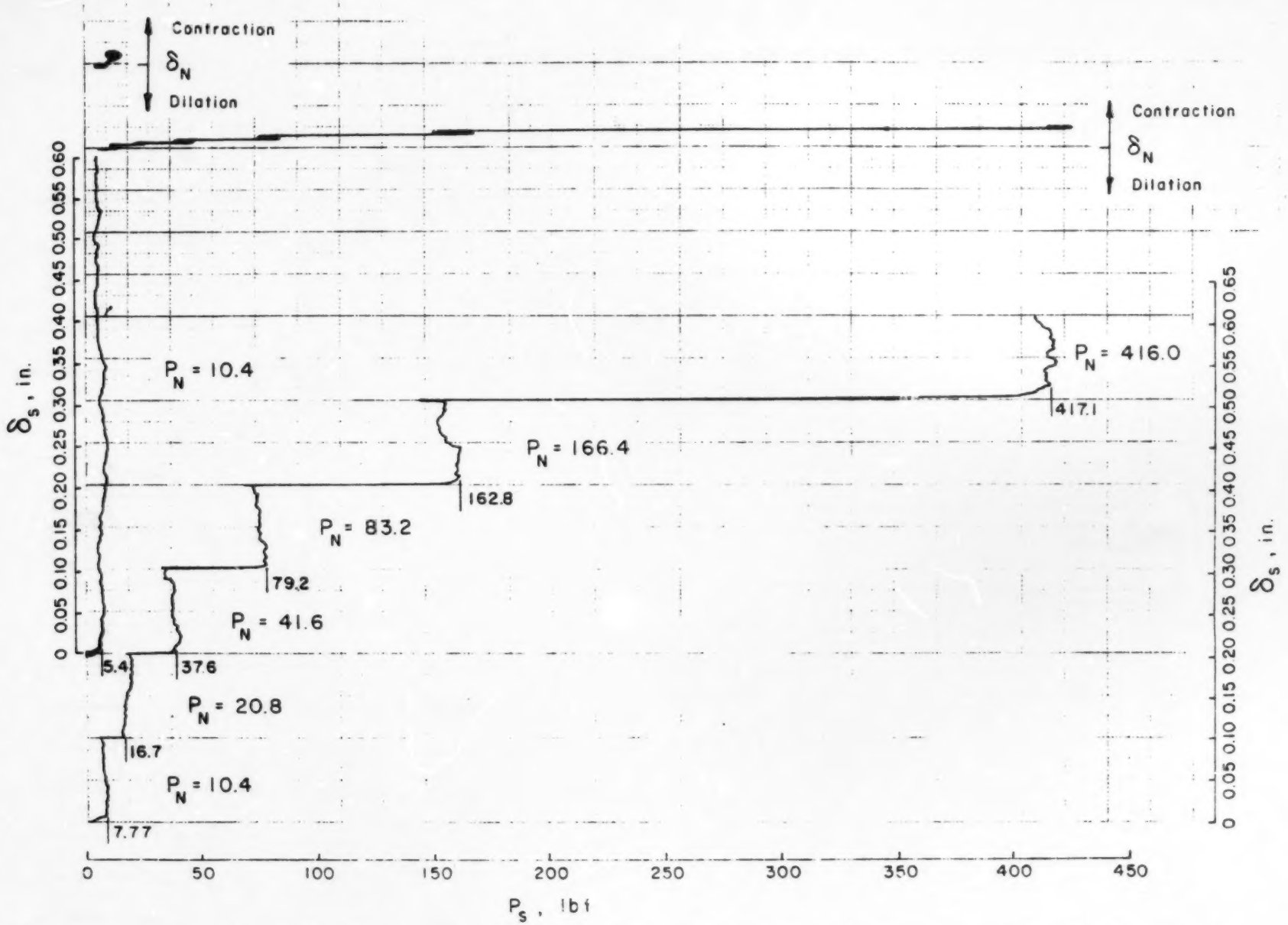

Fig. 9 - Test data, for Indiana limestone with smooth joint, obtained by multi-stage procedure. Test line: 1

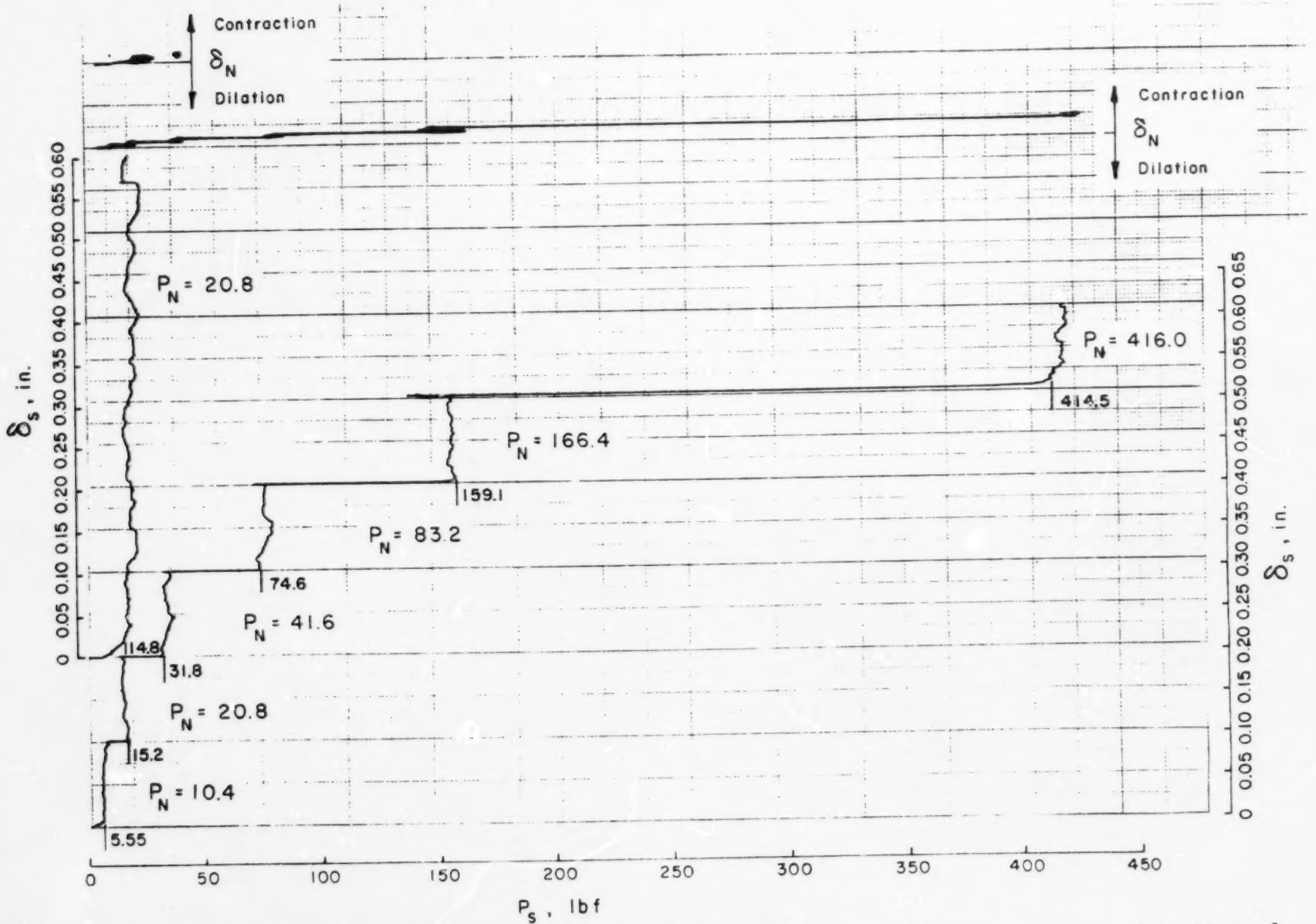

Fig. 10 - Test data, for Indiana limestone with smooth joint, obtained by multi-stage procedure. Test line: 2

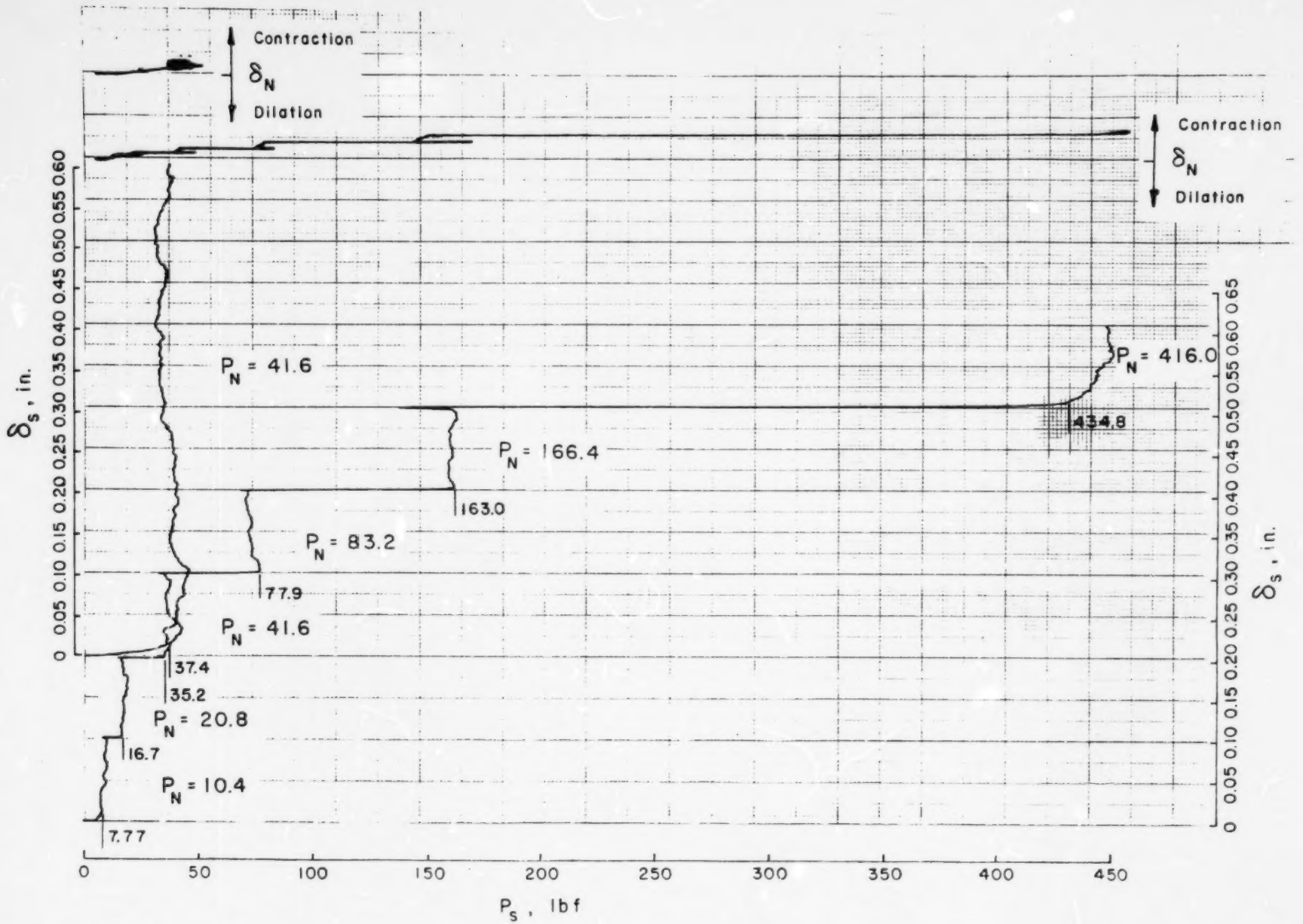

Fig. 11 - Test data, for Indiana limestone with smooth joint, obtained by multi-stage procedure. Test line: 3

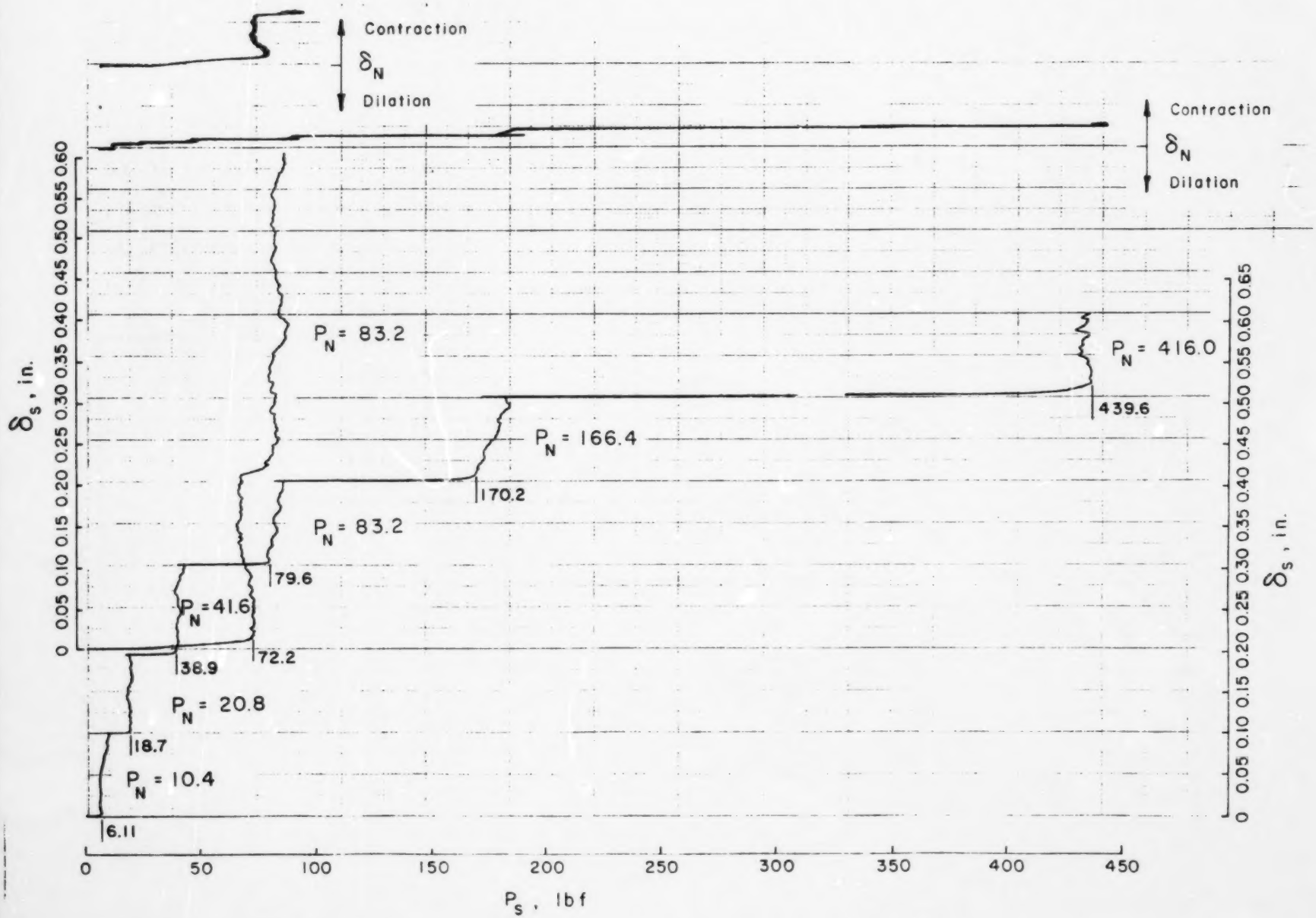

Fig. 12 - Test data, for Indiana limestone with smooth joint, obtained by multi-stage procedure. Test line: 4

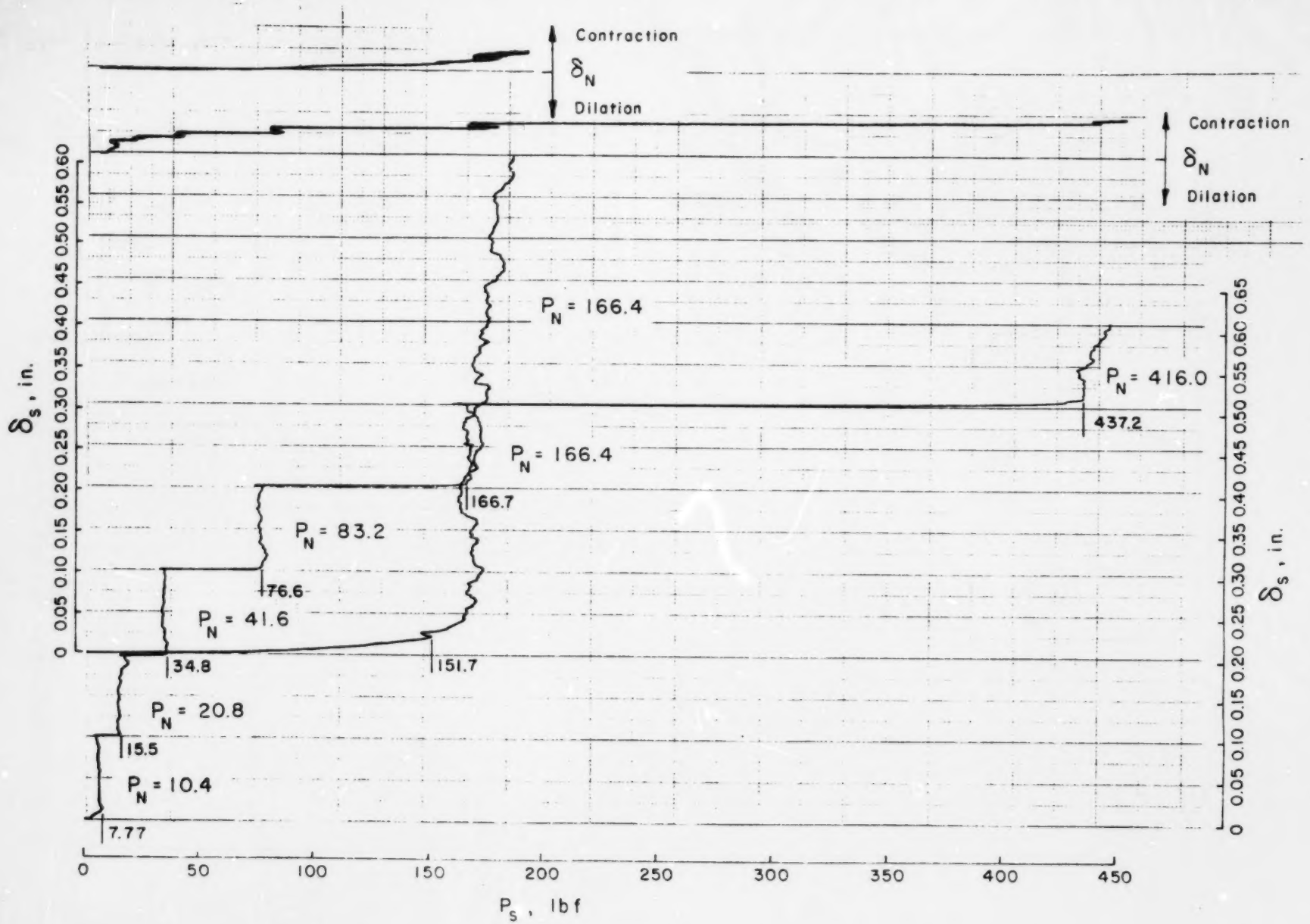

Fig. 13 - Test data, for Indiana limestone with smooth joint, obtained by multi-stage procedure. Test line: 5

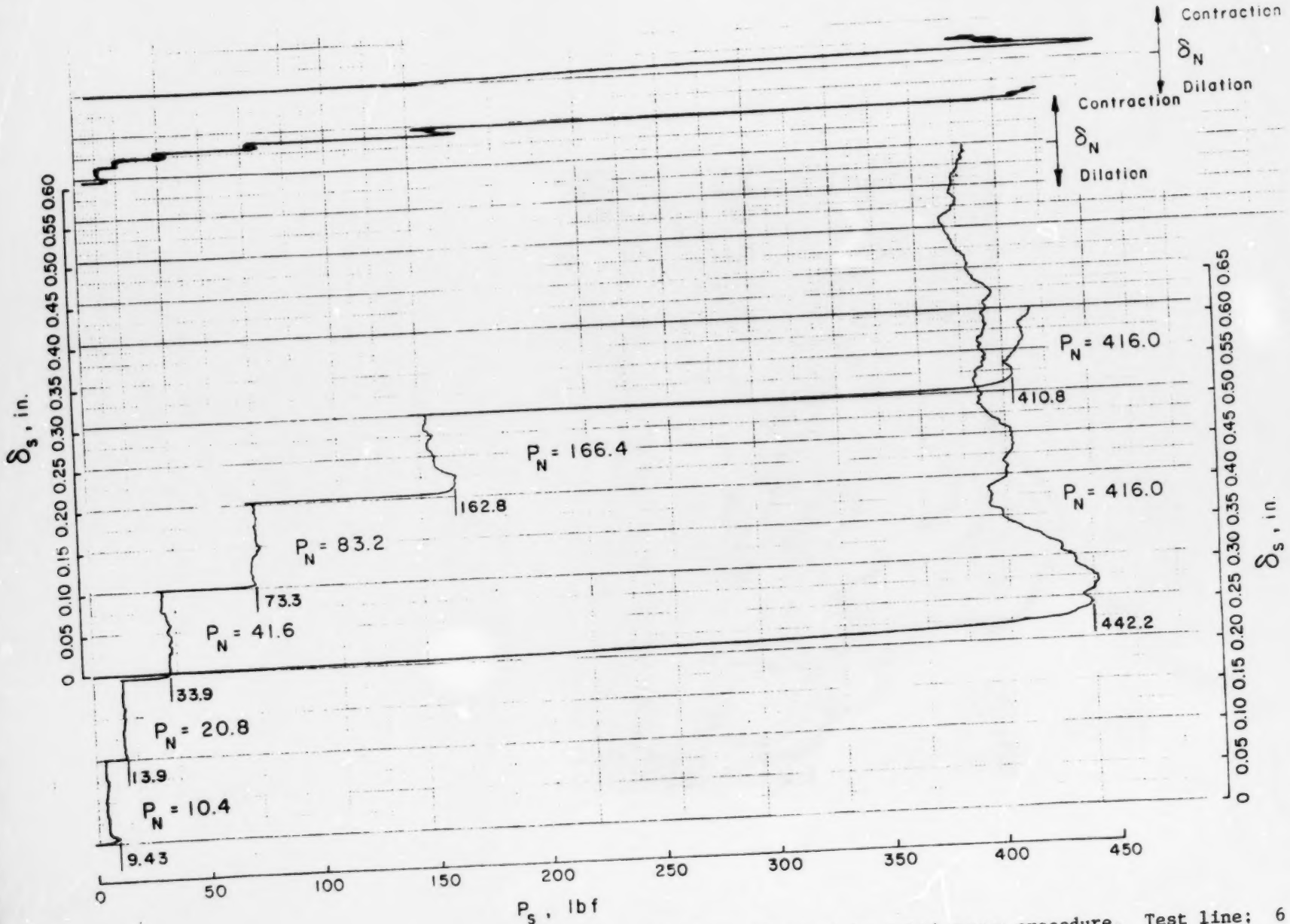

Fig. 14 - Test data, for Indiana limestone with smooth joint, obtained by multi-stage procedure. Test line; 6

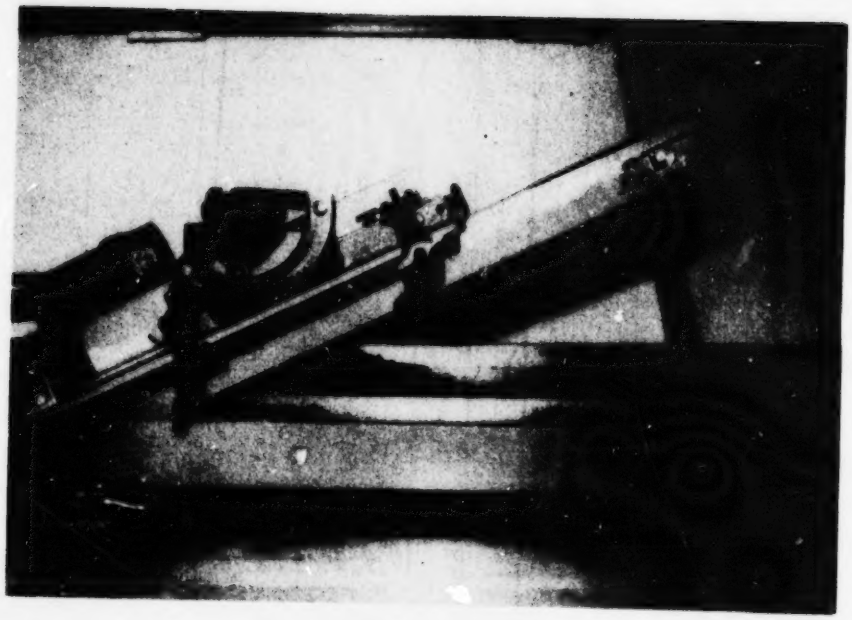

Fig. 15 - Tilt table with cores

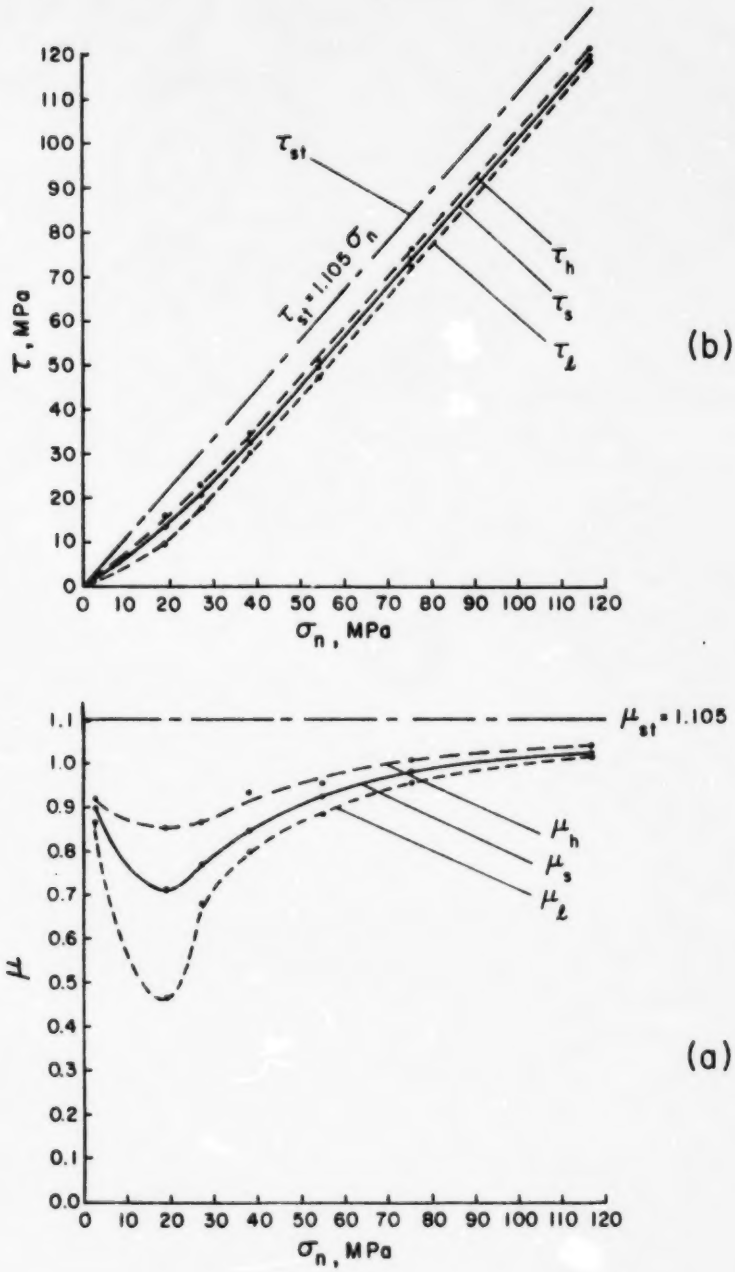

Fig. 39 - Frictional and strength properties of smooth-jointed Indiana limestone; (a) normal stress versus coefficient of friction, (b) normal stress versus shear stress